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University of Michigan
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Unique Results and Lessons Learned from the TSS Missions

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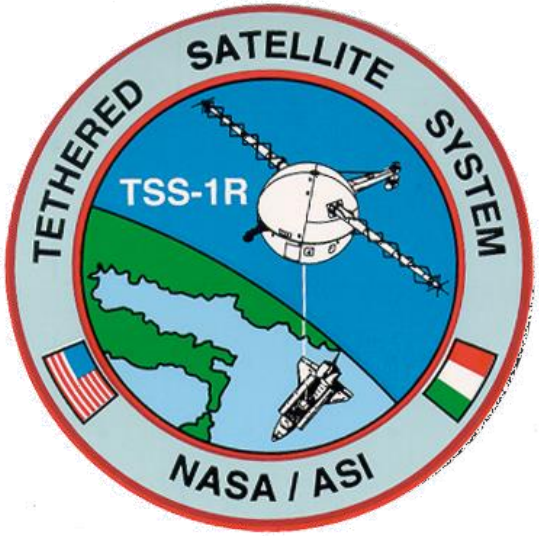
Tether Heritage

General Background



Developmental History of

Space Tethers

1970's	Dynamics of long gravity-gradient stabilized tethers shown feasible and electrodynamics elucidated/ NASA presented TSS concept	Giuseppe Colombo (U. of Padova) & Mario Grossi (SAO)
1979-80	NASA/OSSA Facilities Requirements Definition Team (FRDT)	Peter Banks, chair (U of Mich.)

1980's	NASA OSF Ivan Becky	Technological interests formulated - electrical power generation - orbital transfer - de-orbit, etc.
August 1992	TSS-1 launch	Successful control & damping of dynamics at ~300 m
1993, 1994	SEDS-1 and 2	Successful deployment to 20 km (1) and stabilization (2)
June 1993	PMG	Bi-polar operation (generator and motor modes)
February 1996	TSS-1R Launch	High Voltage Electrodynamics validated/ 3.5 kW power generated/open issues remain
June 1996	TiPS	NRL tether dynamics study. 4 km long x 2 mm diameter tether. Has survived in space 4 years 11 months.
June 2002	ProSEDS	NASA-Marshall demonstration of electrodynamic orbit lowering (canceled).

FRDT: Potential Applications of the TSS

Science Applications

- Direct observation of magnetospheric-ionospheric-atmospheric coupling processes in the 125-150 km region (inaccessible)
- Generation and study of large-amplitude hydro-magnetic waves and magnetic field-aligned currents in space plasma—allowing simulation of celestial body electrodynamics—including processes in the Jovian magnetosphere.
- Generation of high-power VLF and ELF electromagnetic waves within the ionosphere-magnetospheric system
- New, global observation and mapping of crustal geomagnetic phenomena
- Observation of important atmospheric processes occurring within the lower thermosphere

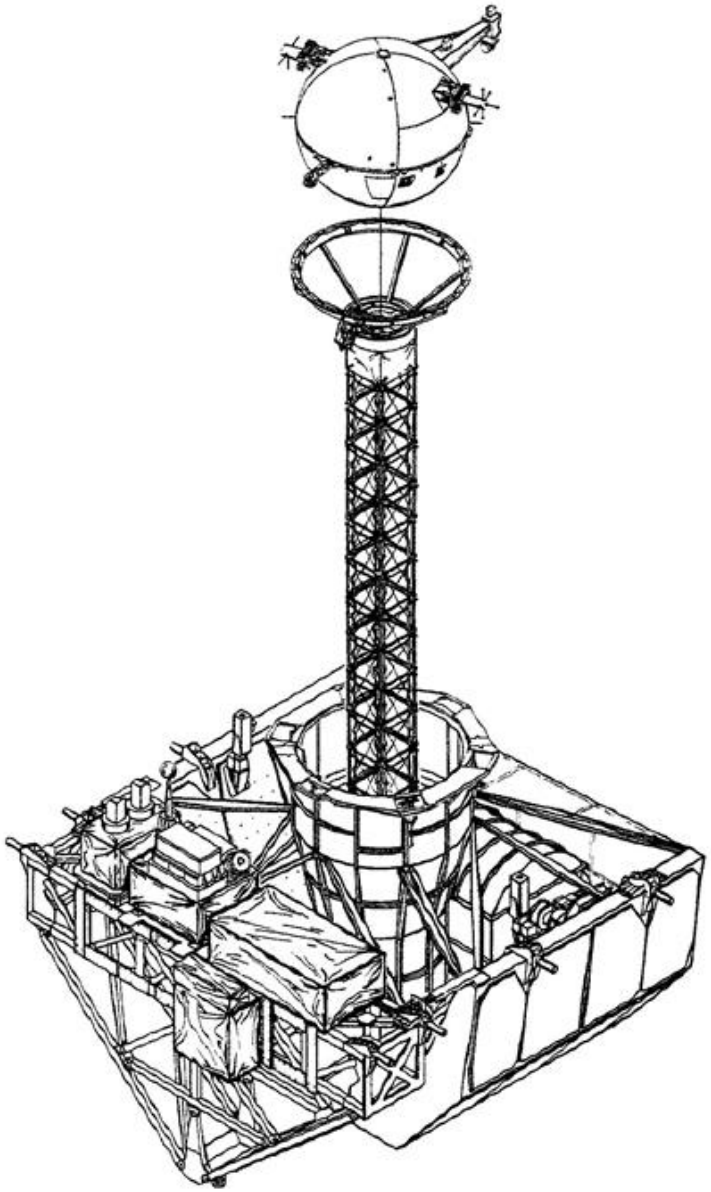
Technology Applications

- The investigation of hypersonic, transition flow aerodynamics (inaccessible)
- Controlled investigation of spacecraft-space plasma environmental dynamics
- Long-wire antennas coupling with the ionospheric plasma
- Electrical Power Generation
- Propellantless Propulsion Generation

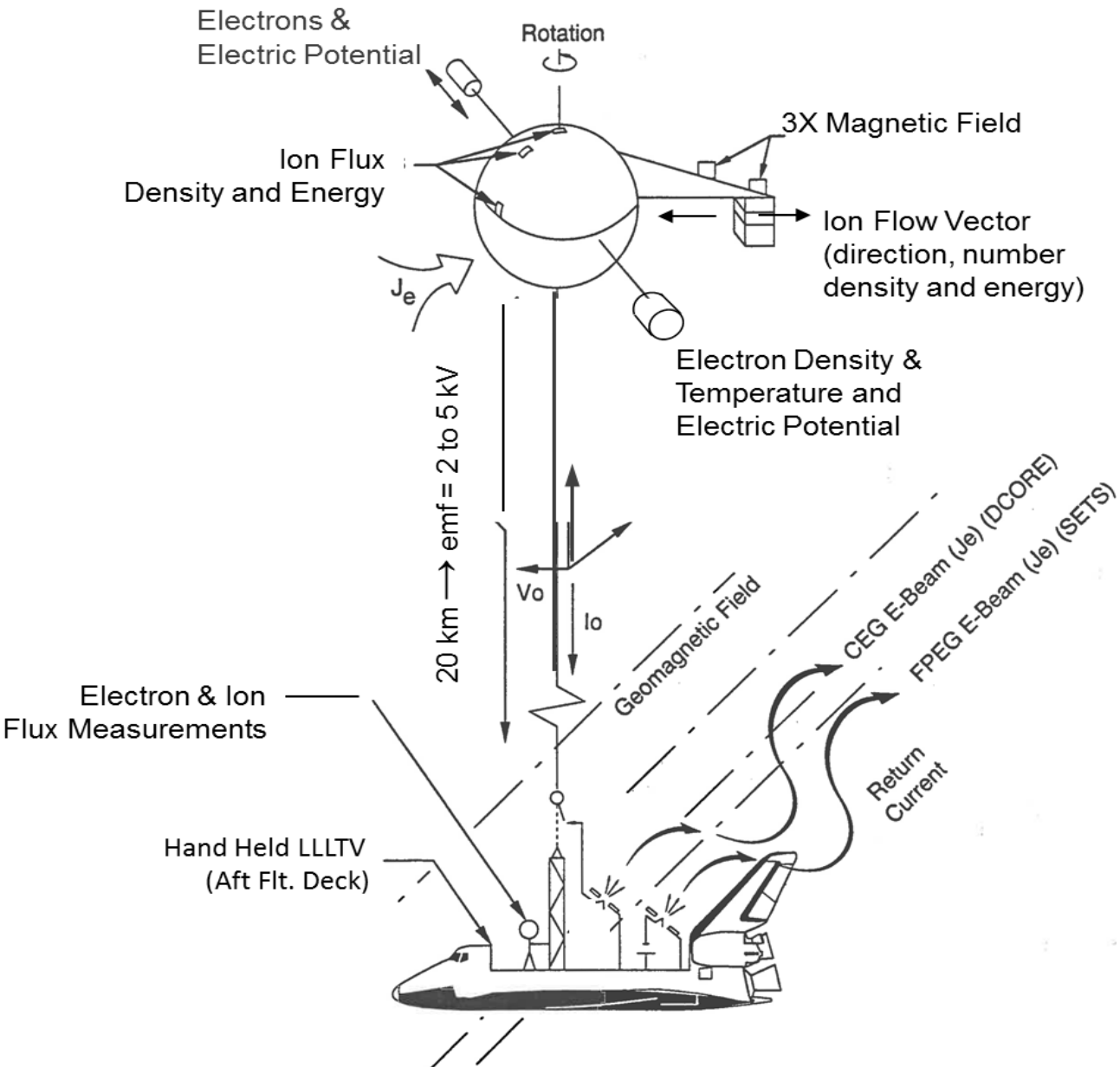
Tether Heritage

The Tethered Satellite System

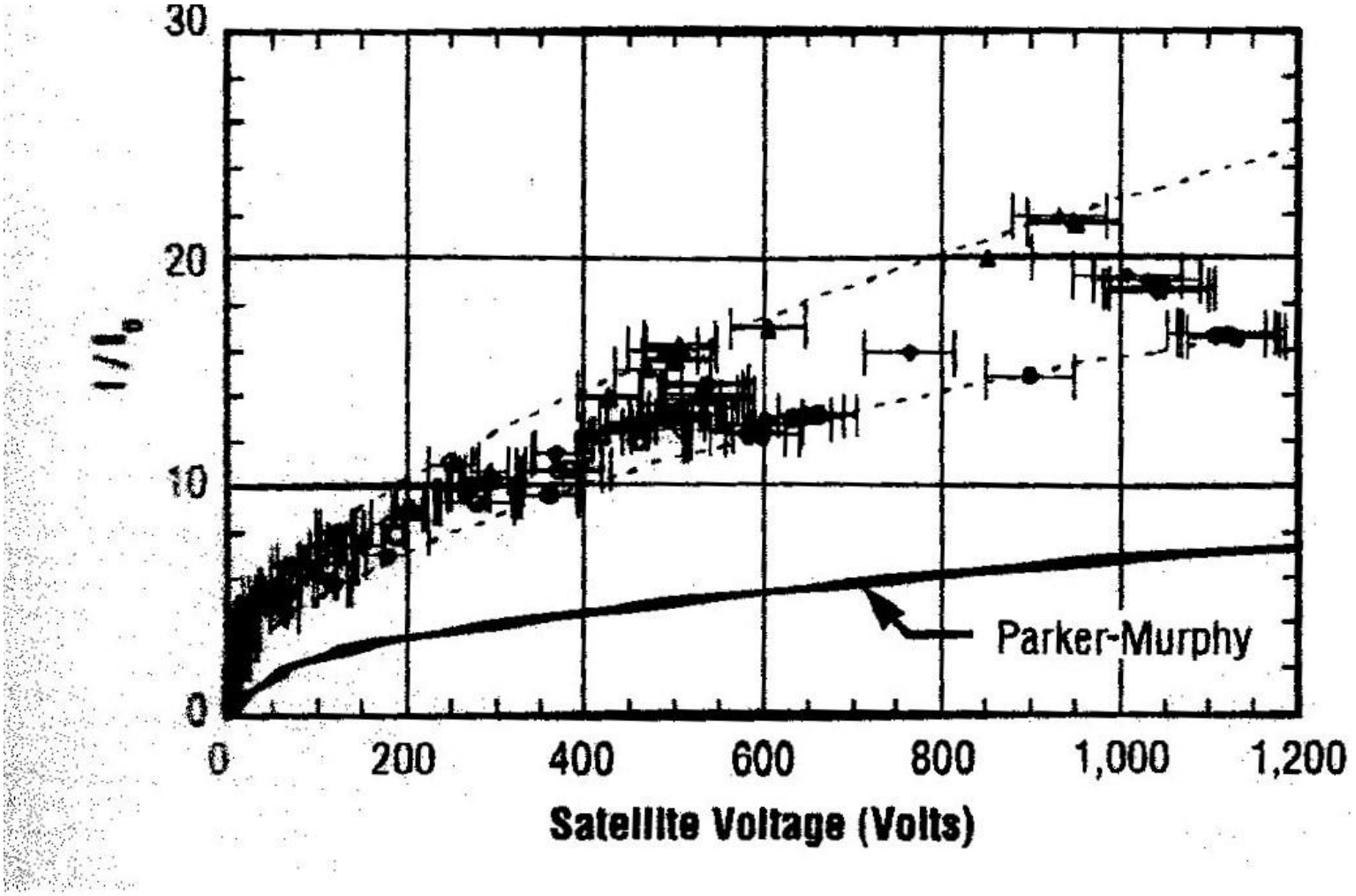
TSS Deployer and Satellite Systems



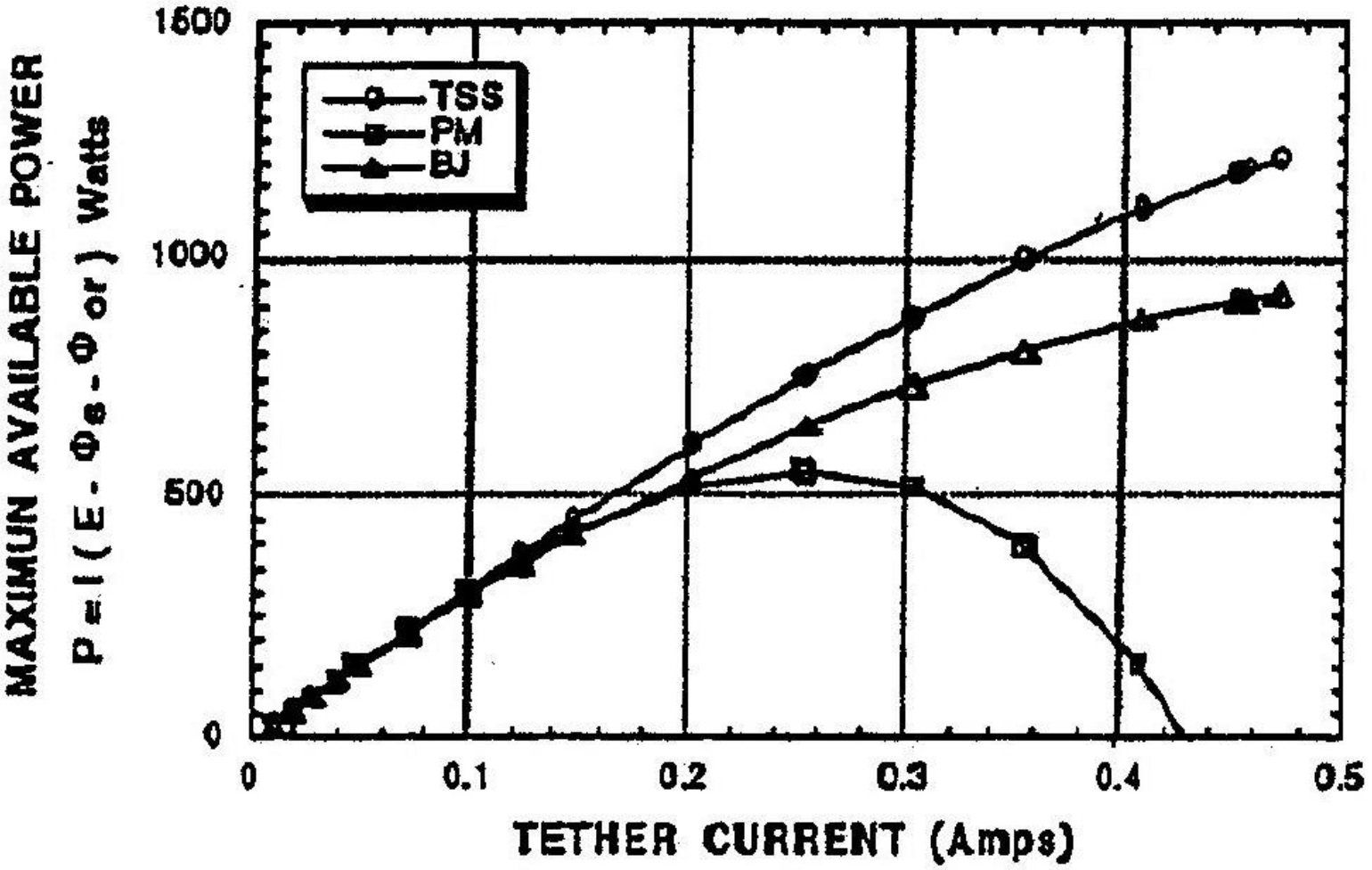
TSS Functional Schematic



TSS-1R Nominal Electrodynamic Data - Current



TSS-1R Nominal Electrodynamic Data - Power



Plasma Motor-Generator (PMG) Experiment

PMG

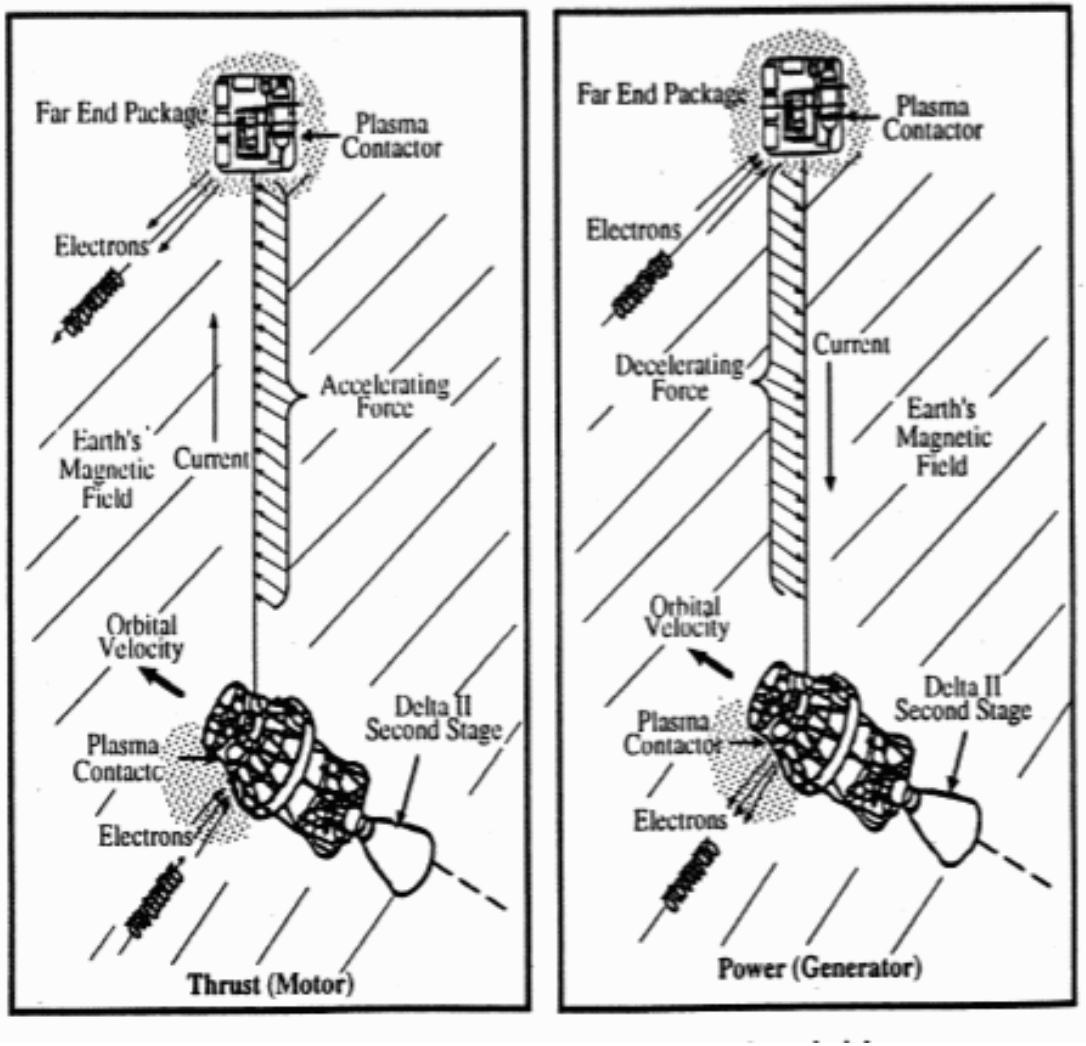
Launched June 26, 1993
on Delta 7925/GPS-39

- **Deployed to full 500 meters using a spring ejection**

  Reached maximum separation with excess velocity, bounced, then settled into a gravity gradient stable position.

- **Successful Bi-directional Operation**

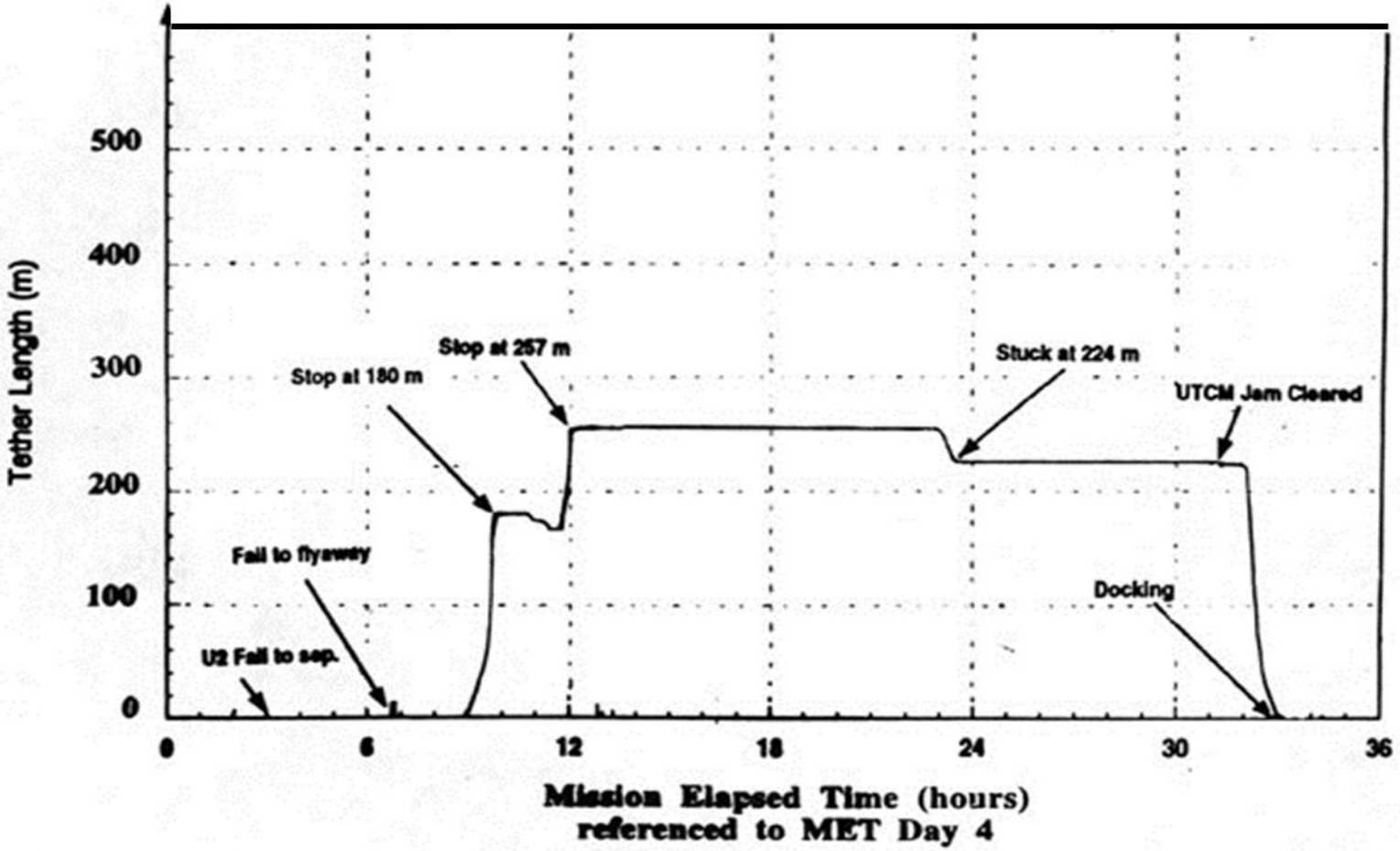
  Polarity and current flow reversal demonstrated using multiple voltage and current steps.



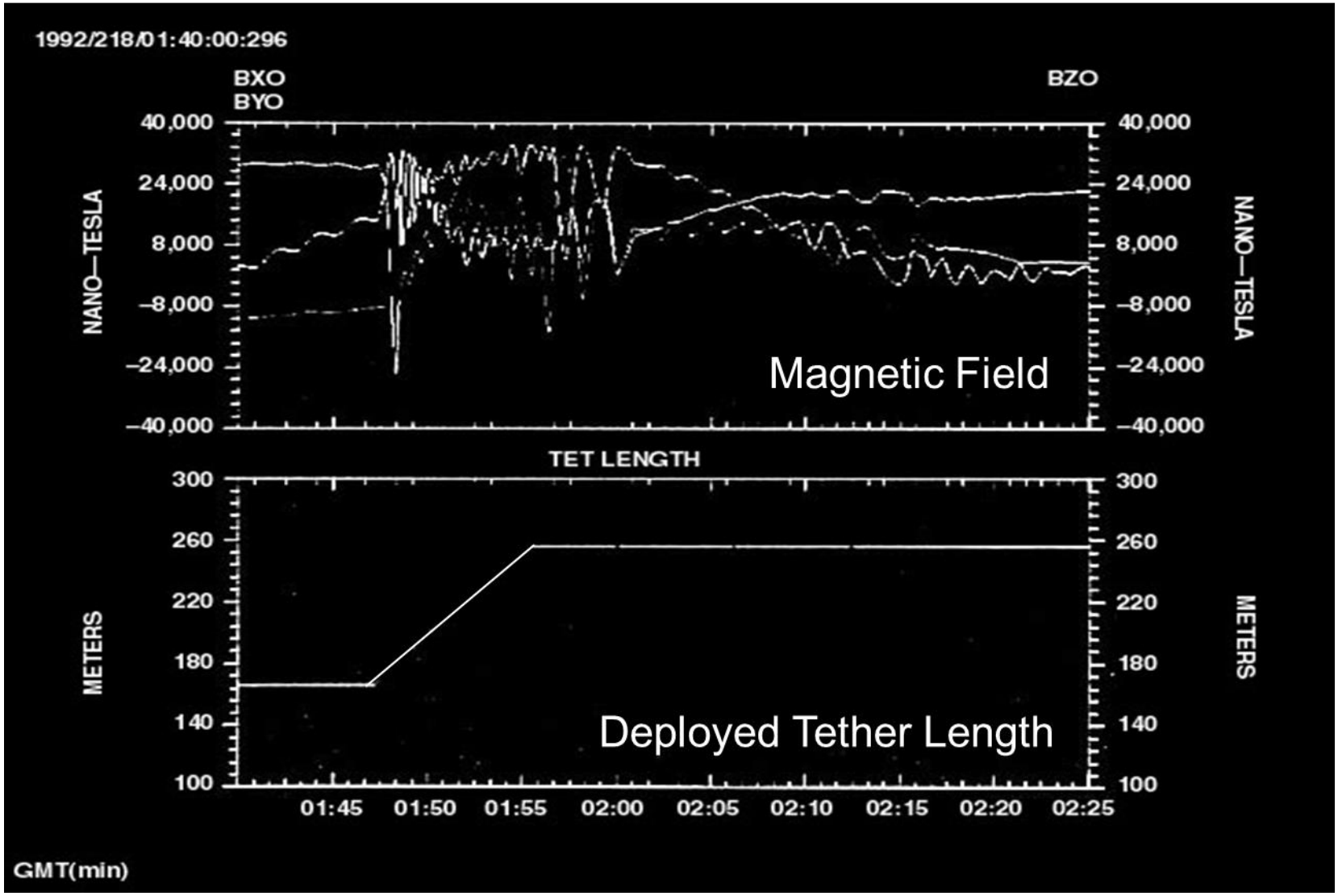
Tether Heritage

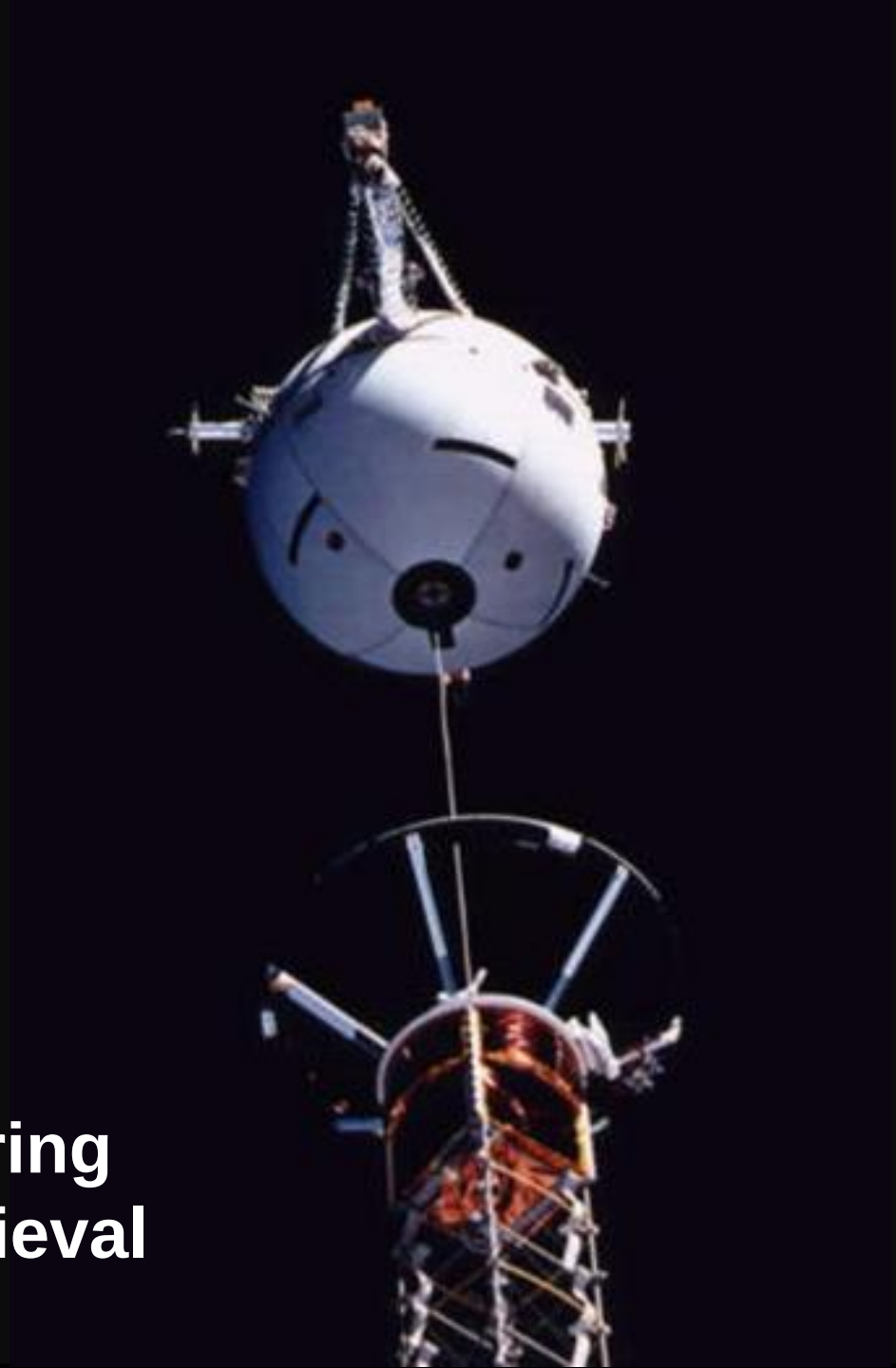
What Went Wrong?

TSS-1 Deployment Profile



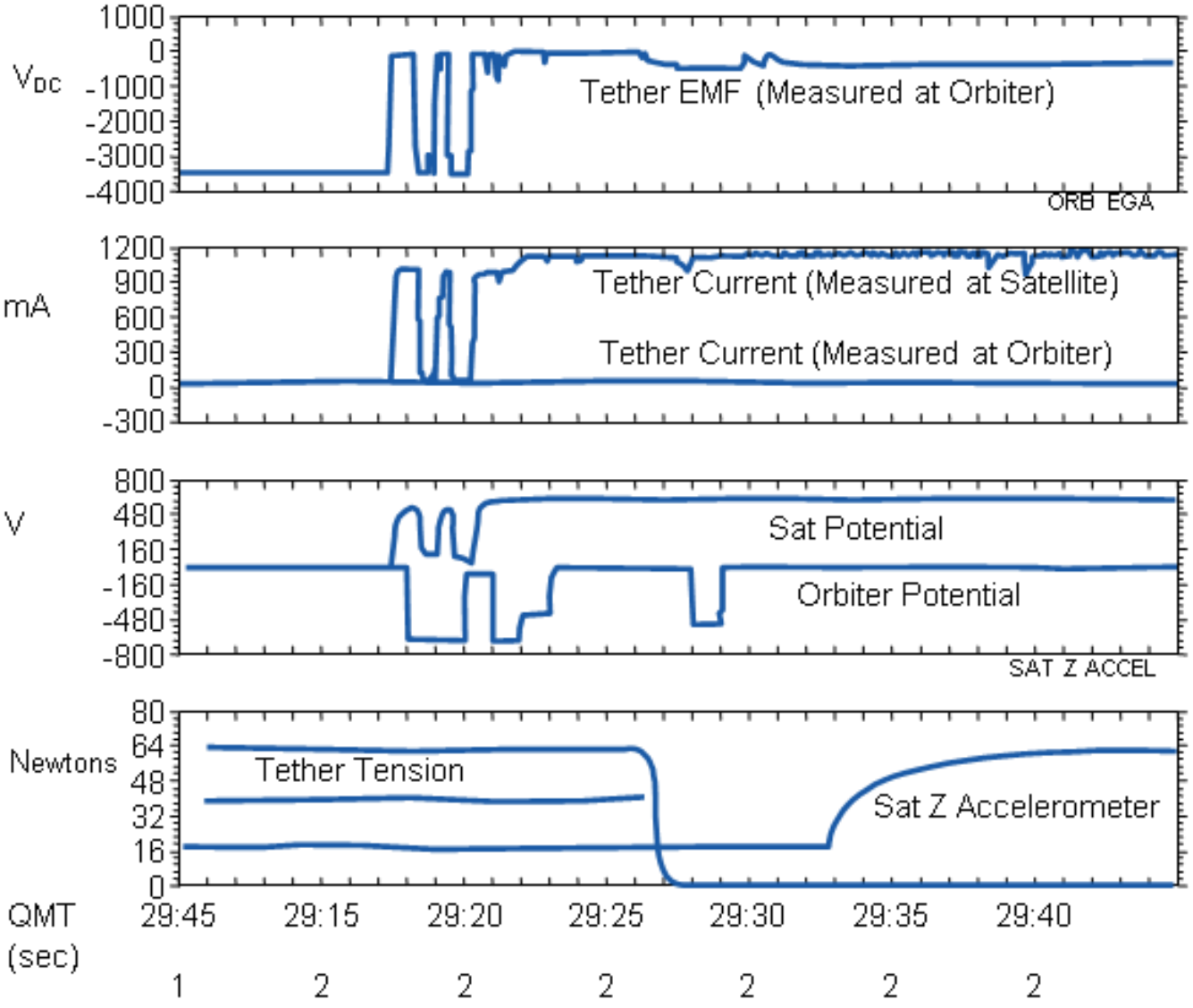
TSS-1 Dynamic Up-Set Event



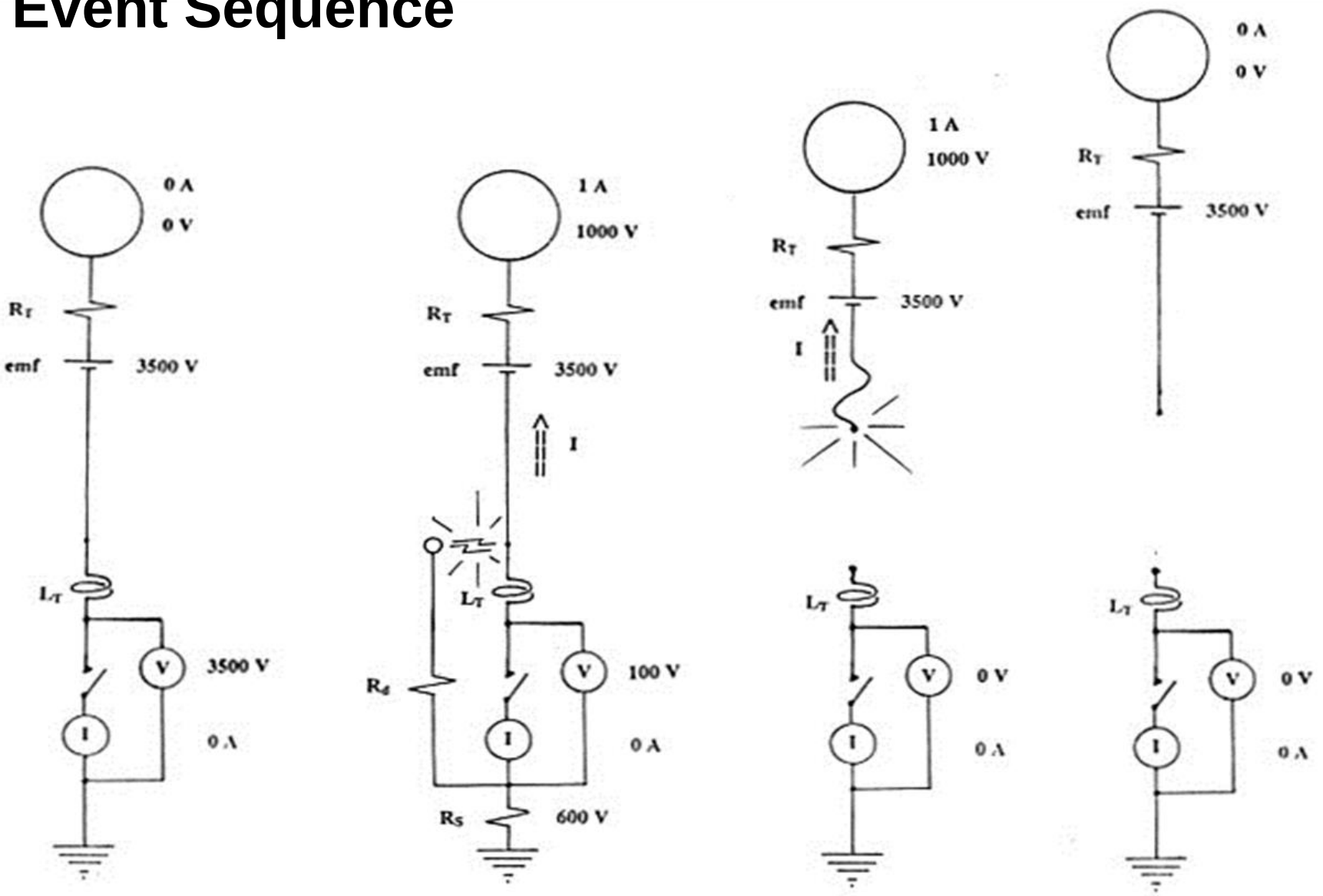


TSS-1 During Final Retrieval

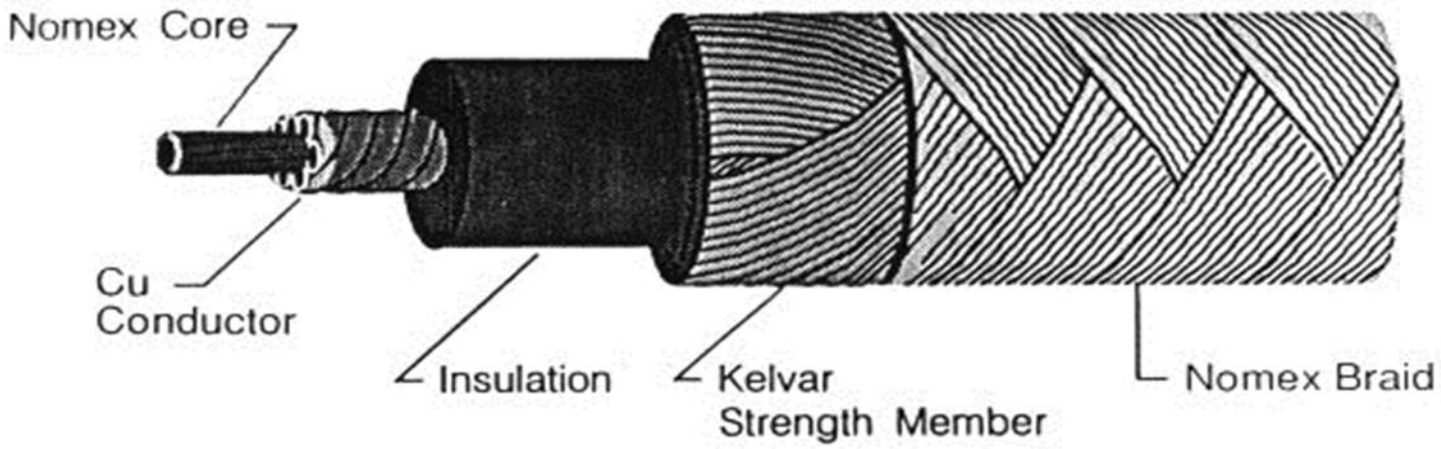
TSS-1R “Tether Break” Event



Schematic of TSS-1R "Tether Break" Event Sequence



TSS-1R Tether Construction



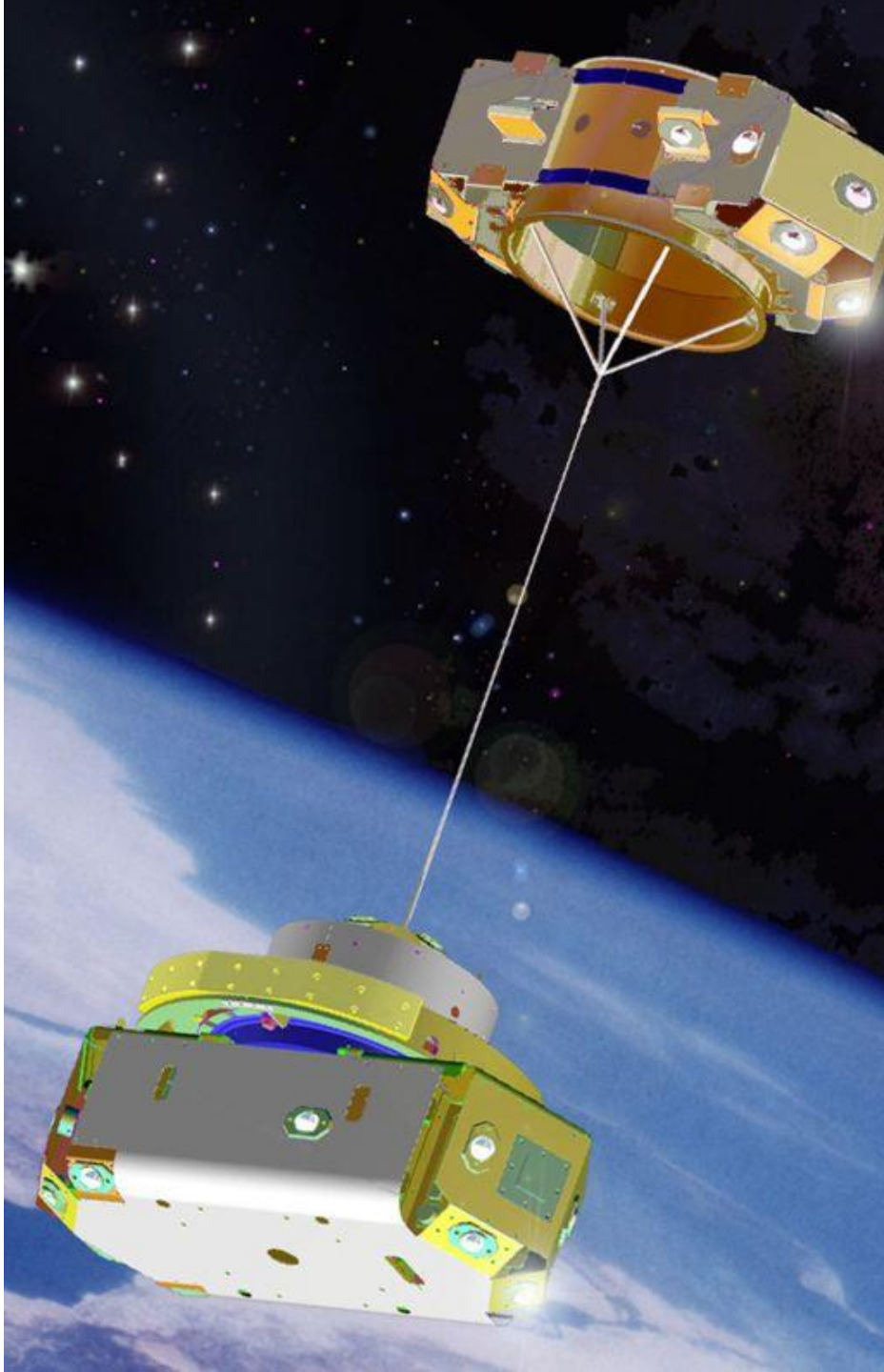
Diameter	2.54 mm (0.1 in)
Max Mass	8.2 kg/km (5.5 lb/kft)
Breakstrength	1780 N (400 lb)
Temp Range	-100° to +125° C (-148° to +257° F)
Elect Characteristics	Carry 1-A Current at 10 kV
	0.2 Ω/m
	5 mA (Max) Leakage
Max Elongation	5% at 1780 N

Are the Problems Resolved?

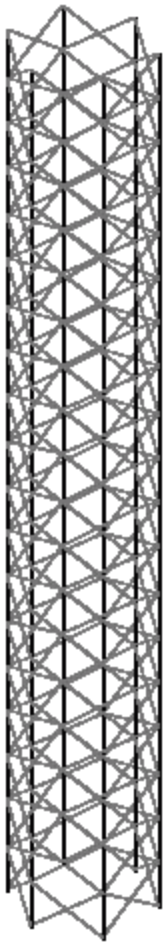
TiPS—a decade on orbit

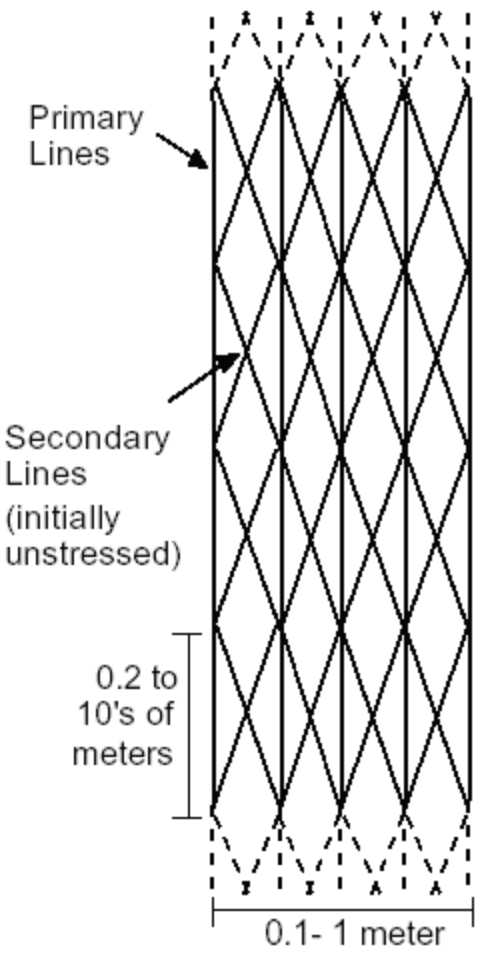
Tether Physics and Survivability Experiment (TiPS):

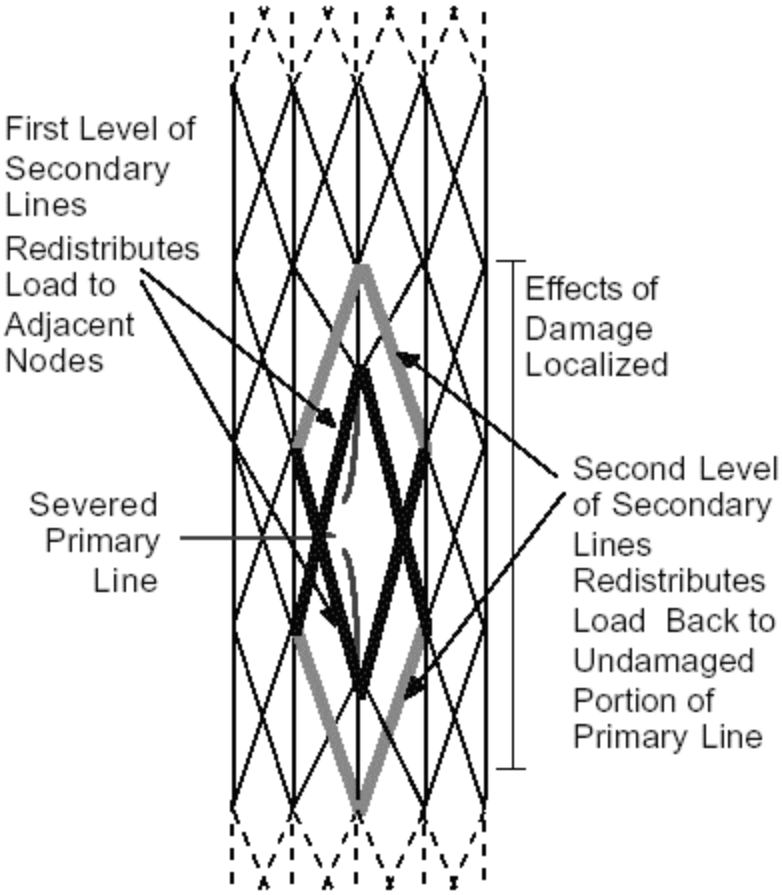
- Launched in 1996 as a project of the US Naval Research Laboratory.
- Deployed 4,000 meter tether.
- Tether broke in July 2006.
- TiPS life on orbit far exceeded model predictions for limited tether life as a result of micrometeoroid impacts.



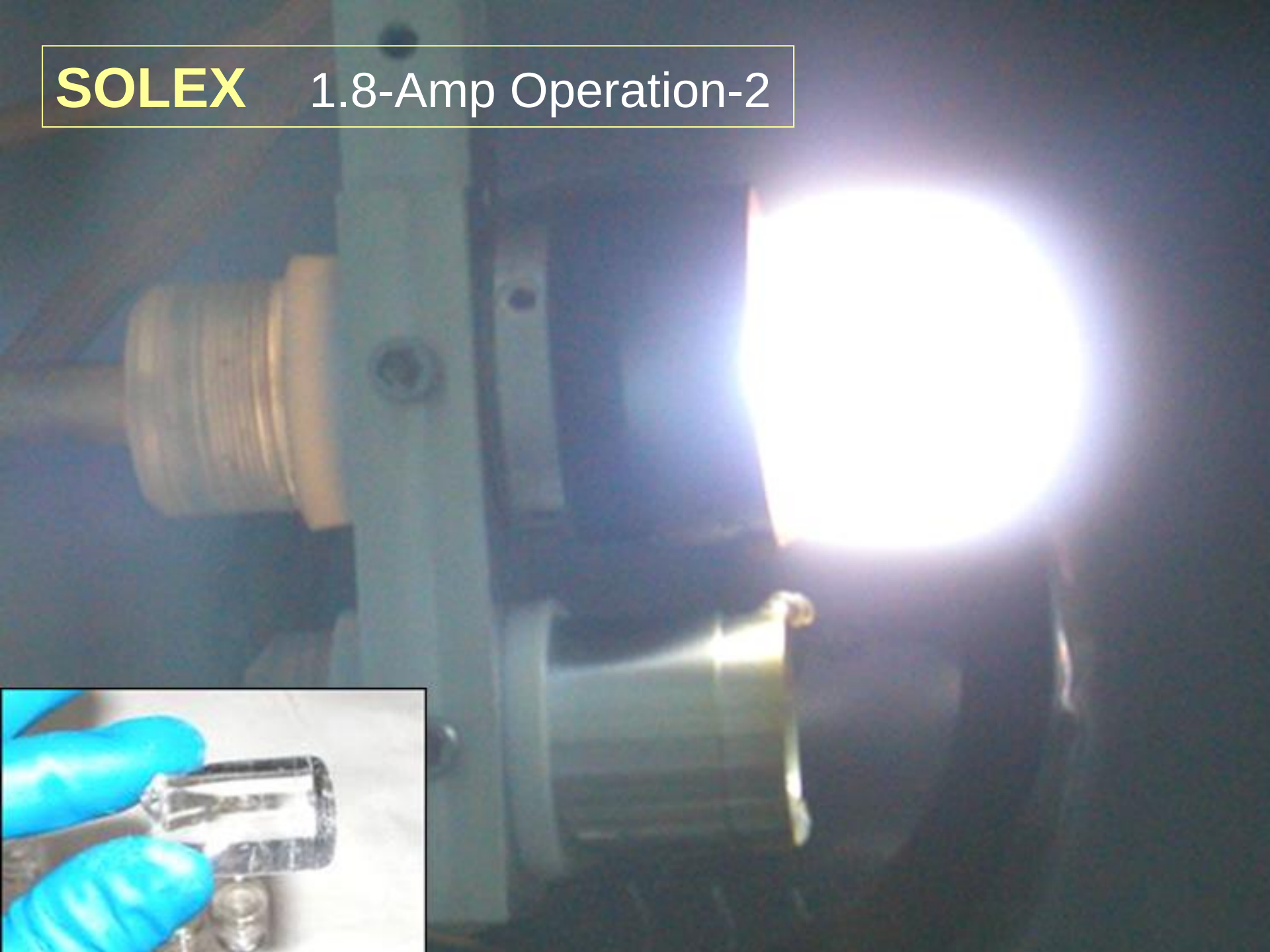
Hoyt Multi-String Tether Concept



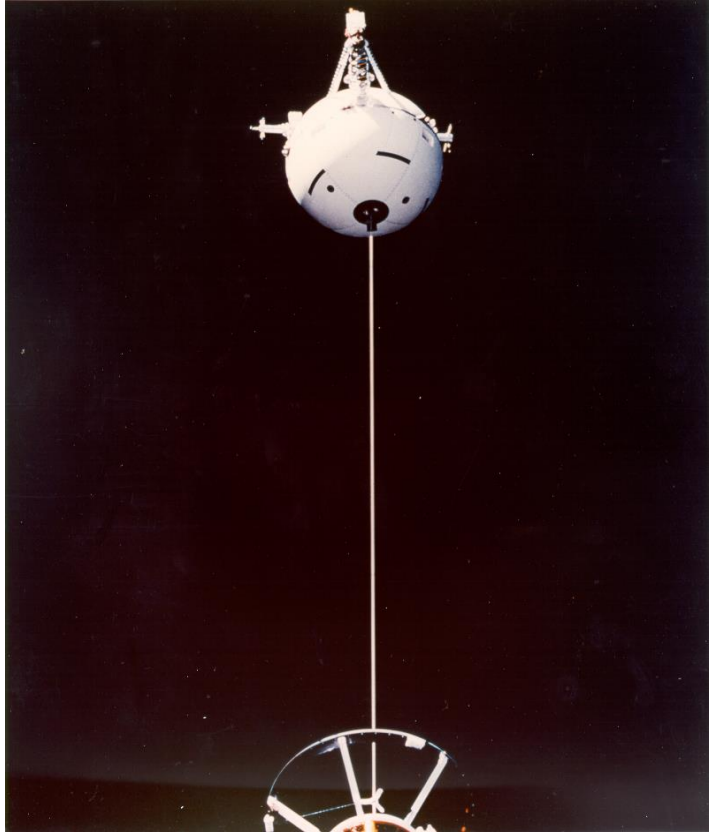




SOLEX 1.8-Amp Operation-2



Results from Tether Missions



Dynamics

- **Dynamic Stability (TSS-1)**
  Gravity-gradient stabilization achieved at < 300 m.
- **Ease of Deployment and Control (SEDS-1/2 & TSS-1)**
  Deployment to 20 km, station keeping for more than 20 hrs, and satellite retrieval have been demonstrated.
- **Recovery from Dynamic Upsets & Slack Tether**
  TSS recovered from severer dynamic perturbations, slack tether and satellite pendulous motions.
- **Retrieval (TSS-1)** Near retrieval (most critical aspect) from 276 m was nominal (shown at right).

Electrodynamics

- **Current collection in space *ten times more* efficient than predicted (TSS-1R)**
  Pre-TSS theoretical models much too conservative.
- **Energy conversion from spacecraft orbit into electrical power demonstrated (TSS-1R)**
  A peak power of > 3.5 kW was generated.
- **Bi-polar operations (PMG)** Polarity and current flow reversal performed, demonstrating power and propulsive thrust generation.

Hardware Flight Heritage

- **Tether Survivability Demonstrated In-Space (TiPS)**
  The TiPS tether (2 mm x 4 km) remains intact on orbit after 4 years-11 months.
- **Deployer In-Space Validation (6 missions)**
  Successful deployment with simple spool deployer (SEDS-1 & 2, PMG and TiPS), and with real type (TSS)

What is the Future of Space Tethers?